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6P3.0 GRAVITY WAVES IN THE MIDDLE ATMOSPHERE:
RECENT PROGRESS AND NEEDED STUDIES

David C. Fritts

Geophysical Institute
andDepartment of Physics
University of Alaska

Fairbanks, Alaska 99775-0800

AM 841 926

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INTRODUCTION

The recent recognition of the important role played by gravity waves in the large-scale circulation and thermal structure of the mesosphere and lower thermosphere (HOUGHTON, 1978; LINDZEN, 1981) has stimulated considerable research on their properties and their middle atmosphere effects. For example, these studies have begun to provide important information on gravity wave scales, propagation, filtering, and the processes responsible for saturation and turbulent diffusion. There remain, however, many areas in which our current understanding of middle atmosphere gravity waves is deficient. The purposes of this paper are to review the progress that has been made to date and to suggest areas in which additional studies are most needed.

Major motivations for studies of gravity waves in the middle atmosphere, of course, are the roles of such motions in providing both a drag on the large-scale flow and a turbulent diffusion that acts on the heat and constituent distributions as well as the need to incorporate these effects in dynamical, chemical, and radiative models of these regions. In the mesosphere and lower thermosphere, gravity-wave drag results in a reversal of the vertical shear of the zonal mean wind, driving a strong mean meridional circulation and a reversal of the mean meridional temperature gradient near the mesopause. The effects of gravity-wave drag in the stratosphere, while not as significant as at higher levels, appear to be important nevertheless in maintaining the large-scale circulation of this region. Likewise, turbulent diffusion due to gravity wave saturation contributes significantly to maintenance of the heat and constituent distributions in the mesosphere and lower thermosphere and may be important in the stratosphere as well. The theory and observations relating to gravity-wave saturation were reviewed by FRITTS (1984).

RECENT PROGRESS IN GRAVITY-WAVE STUDIES

A number of studies in the last few years have addressed various aspects of gravity-wave propagation, saturation, and effects in the middle atmosphere. As a result, we are beginning to understand in more detail the role of gravity waves in middle atmosphere dynamics. Several studies have examined gravity-wave scales and phase speeds, yielding an indication of those wave motions that are likely to be most important in the middle atmosphere (VINCENT and REID; 1983; SMITH and FRITTS, 1983; MEEK et al., 1985a). Typical motions were found to have horizontal wavelengths that range from ~ 10 to 10^3 km, observed periods of ~ 10 to 10^3 min, and phase speeds of ~ 10 to 10^2 ms^{-1} . In most cases, these values were associated with wave motions having vertical scales $\gtrsim 10$ km due to resolution constraints of the various observing systems. There is also evidence, however, of motions with much smaller vertical scales, and likely much smaller horizontal scales and phase speeds as well, from high-resolution rocket, radar, and balloon soundings of the stratosphere, mesosphere, and lower thermosphere (PHILBRICK et al., 1983; FRITTS et al., 1985; SATO and WOODMAN, 1982a; BARAT, 1983; and others).

Other studies have examined the mechanisms responsible for gravity-wave saturation in the middle atmosphere and the amplitude limits implied by these mechanisms. The dominant saturation mechanisms appear to be convective and dynamical instabilities, with nonlinear wave-wave interactions contributing, perhaps, at small vertical scales (FRITTS and RASTOGI, 1985). These wave field instabilities seem to limit wave amplitudes, as assumed by HODGES (1967) and LINDZEN (1981), but to amplitudes somewhat smaller than monochromatic saturation values due to wave superposition (ORLANSKI and CERASOLI, 1981; FRITTS, 1985). Indeed, the amplitude limits imposed by saturation appear now to account for the shape of the vertical wave number spectrum of gravity-wave motions (DEWAN and GOOD, 1985; SMITH et al., 1985) and thus may explain the apparent universality of the atmospheric motion spectrum (VANZANDT, 1982). These studies have also shown the gravity-wave spectrum to be saturated throughout the lower and middle atmosphere, with a characteristic vertical scale and energy that increase with height (SMITH et al., 1985).

We are also beginning to understand the processes responsible for turbulence production and turbulent diffusion. These are the convective and dynamical instabilities mentioned above, and they appear, in many instances at least, to result in the generation of strong, local turbulence at preferred locations within the wavefield (SATO and WOODMAN, 1982b; BALSLEY et al., 1983; BARAT, 1983; COT and BARAT, 1985; FRITTS et al., 1985). The convective instability is thought to predominate for high-frequency wave motions (with $\omega \gg f$) while the dynamical instability appears more likely for low-frequency motions (with $\omega \sim f$). In either case, the wave motion is believed to be most unstable where T' is a minimum rather than where u_z' is a maximum (FRITTS and RASTOGI, 1985). The resulting distribution of turbulence throughout the wave field appears to result in a large turbulent Prandtl number (JUSTUS, 1967) and a reduction of the effective turbulent diffusion of heat and constituents due to gravity-wave saturation (FRITTS and DUNKERTON, 1985; STROBEL et al., 1985).

Finally, recent studies have begun to address the distributions of gravity wave energies and momentum fluxes with height and time. Studies of the former by MEEK et al. (1985b) and VINCENT and FRITTS (1986) suggest significant seasonal variations as well as short-term fluctuations. The seasonal variations of gravity-wave energies correlate well both with variations in the turbulent diffusion of H_2O inferred from SME O_3 fluctuations (THOMAS et al., 1984) and with observed seasonal variations of turbulence intensities (Vincent, private communication, 1985). Short-term fluctuations appear to correlate with variations in the mean winds at lower levels.

Observational studies of gravity-wave momentum fluxes by VINCENT and REID (1983), REID (1984), and FRITTS and VINCENT (1985) have provided estimates of zonal accelerations due to gravity-wave drag $\sim -50 \text{ ms}^{-1}\text{day}^{-1}$, largely consistent with expectations based on the observed zonal wind structure (HOLTON, 1983). In addition, the latter studies have found considerable variability of the momentum flux due to high-frequency gravity waves with time-of-day, suggesting a modulation of this flux by tidal motions. A model of the modulation and of its implications for mean flow accelerations and tidal measurements was proposed by FRITTS and VINCENT (1985). This study also found the majority ($\sim 70\%$) of the gravity-wave momentum flux and flux divergence to be associated with motions with periods $< 1 \text{ hr}$, suggesting that the dominant flux is due to motions with small horizontal scales as well (VINCENT and REID, 1983).

NEEDED STUDIES

The gravity-wave studies described above have contributed substantially to our knowledge of the role of such motions in middle atmosphere dynamics. However, there remains a great deal that is unknown or poorly known concerning gravity-wave propagation, saturation, and effects in the middle atmosphere.

The purpose of this section is to highlight several areas in which our knowledge is particularly limited.

As noted above, some attention has focused on the dominant gravity-wave scales in the middle atmosphere, but the identified motions number only ~ 100 . And because these studies were performed at only a few locations, the results may not be representative of the global gravity-wave distribution. Most observational facilities are located in or near mountainous terrain, which might bias wavelength and/or phase speed distributions. Preliminary motion spectra in the equatorial Pacific, for example, exhibit a somewhat different character than those obtained over significant topography (BALSLEY, personal communication, 1985).

The character of the gravity-wave spectrum will have a major influence on the response of the middle atmosphere, however, and should serve to motivate additional studies of this sort, hopefully representing a more diverse global coverage than is presently available. An indication of the geographic variability of gravity-wave sources and of the middle atmosphere response is provided by the model studies of MIYAHARA et al. (1985), which show considerable variability in the gravity-wave momentum flux extending to upper levels due to localized regions of convective activity. And this is in a model that does not resolve what are now thought to be the dominant temporal and spatial scales (FRITTS, 1984). Presumably, smaller spatial scales would produce even more localized middle atmosphere effects.

Other areas of major uncertainty are the causes and effects of variability of the gravity-wave spectrum. Variability imposed by planetary-wave motions were examined by DUNKERTON and BUTCHART (1984), HOLTON (1984), SCHOEERL and STROBEL (1984), and MIYAHARA et al. (1985). Observational studies have likewise provided evidence of considerable variability of gravity-wave energies, momentum fluxes, and turbulent diffusion (REID, 1984; THOMAS et al., 1984; MEEK et al., 1985b; VINCENT and FRITTS, 1986; FRITTS and VINCENT, 1985; FRITTS et al., 1985). Yet our knowledge of these processes remains primitive due to the extremely limited observations. Of particular importance, perhaps, are observations addressing the variability due to gravity-wave sources and filtering, as these appear to operate on the planetary-wave scales of relevance to the middle atmosphere circulation and structure.

Another area requiring additional study is the generation and subsequent evolution of turbulence resulting from gravity-wave saturation. Again, while preliminary studies of the mechanisms responsible for turbulence generation have been performed, we know little about either the primary products of turbulence decay (secondary gravity waves, 2-D turbulence, or heat), and thus their role in middle atmosphere dynamics, or the role of such turbulence in the diffusion of heat and constituents.

Finally, our understanding of the role of nonzonally propagating gravity waves is very limited. Most numerical and observational studies to date have considered primarily zonal propagation in zonal flows. Yet there is no reason to suppose that meridionally propagating motions are not equally important. Indeed, studies by SMITH and FRITTS (1983), MEEK et al. (1985a), and VINCENT and FRITTS (1986) indicate that meridional propagation may be preferred, perhaps due to zonal filtering by large zonal winds.

Thus, there are numerous valuable studies remaining to be done which may keep us all busy for quite some time.

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TOPIC 3 SUMMARY: GRAVITY WAVES AND TURBULENCE

Papers presented in this session revealed that we have made considerable progress in understanding a number of important problems concerning gravity wave and turbulence processes in the lower and middle atmosphere since the last MST workshop. Advances were made in understanding the spectral description of the motion field, including the effects of anisotropy and Doppler shifting on gravity-wave spectra, the mechanisms leading to saturation and their effects on wave amplitudes and turbulence intensities, and the causes of the apparent universality of the gravity-wave spectrum and the variation of this spectrum with height. Other studies revealed significant variability of gravity-wave and turbulence parameters and effects, on small to large (annual) temporal scales, associated with changing forcing conditions or propagation environments. Of particular significance in this regard were annual climatologies of gravity-wave energy and turbulence intensity in the mesosphere suggesting a reduction of turbulent diffusion during equinoxes. Evidence was also provided that the more dynamically significant gravity-wave motions (in terms of energy and momentum transports) are those with small horizontal wavelengths (< 200 km) and high intrinsic frequencies. Finally, a number of studies addressed characteristic gravity-wave and turbulence parameters and their variability as well as various means to distinguish between gravity-wave and turbulence motions.

Despite recent progress in understanding gravity-wave and turbulence processes, there remains much that is not known about these motions, their variability, and their effects in the lower and middle atmosphere. Particularly important in this regard are studies (both case studies and climatologies) that address gravity-wave sources, including the dominant temporal and spatial scales and phase speeds, and their long- and short-term variability.

It is important to examine, with whatever systems are available, the climatologies and variability of gravity-wave energy and momentum fluxes and the role of turbulence in the diffusion of heat and constituents throughout the atmosphere. A major factor in the annual climatologies of gravity waves and turbulence in the mesosphere, and one requiring considerable study, is the filtering of the gravity-wave spectrum by local mean winds at lower levels, which causes significant modulations in the energy and momentum fluxes (and in the associated turbulent diffusivities) at higher levels.

The momentum flux divergence due to gravity waves is also likely to be important in the upper troposphere and stratosphere, though the magnitude is expected to be much smaller on average than in the mesosphere and contributions due to various sources may be very localized. This requires high-resolution observations capable of inferring these contributions in a wide range of conditions and locations. It is also important to exercise care in estimating the momentum flux due to mountain waves as these motions are nearly stationary and may not be able to be studied using the dualbeam technique on short time scales.

In addition, further studies are required of the mechanisms and effects of gravity-wave saturation and of the evolution of the motion spectrum by processes other than gravity-wave filtering. With a little luck, our progress in understanding these motions in the next two years will be as significant as in the last two!